BELLCOMM, INC.

SUBJECT: Implications of Spacecraft 011 Flight Results on the Credibility of RCS Propellant Consumption Predictions Case 330

DATE: January 5, 1967

FROM: J. J. O'Connor

ABSTRACT

An examination of the postflight data* of Spacecraft 011 on Mission AS-202 (August 25, 1966) has raised serious questions about the following features of the Reaction Control Systems:

1. The propellant loads of individual tanks were reported to be 1 to 3 percent less than nominal. The cause of this off-loading is not stated, and the capability to measure to this accuracy is questionable.

2. Propellant consumption was estimated by the two techniques of summing engine firings and pressure-volume-temperature gaging. The two percent accuracy claim for the technique which sums engine firing durations is not explained. The temperature-time history needed to correlate the gaging data of the helium pressure measurement technique is not presented.

3. Maneuver dynamics predictions could only be verified to the 10 percent accuracy of the measurement data. Unless vehicle maneuver accelerations can be measured more accurately, it may not be possible to make meaningful comparisons of various attitude control strategies.

4. Propellant consumption for individual maneuvers differed from the predictions by factors of 2, 10, and 25. The reasons for such large discrepancies are not apparent.

5. Total consumption was 34 percent less than predicted. The components of this prediction error are not identified for individual evaluation nor is the acceptability of this prediction accuracy discussed.

If these various difficulties prove to be actual, they could impact the planning for the long-duration AS-204 flight and even the lunar landing mission. Attention is directed toward these results to maximize the usefulness of flight data, and a unified study is suggested to resolve the difficulties.

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*Including corrections to the postlaunch report which were issued by MSC in December.

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MEMORANDUM FOR FILE

1. Introduction

There has been a great deal of activity and controversy about the propellant budgets for the various Reaction Control Systems (RCS) of the Apollo spacecraft.[1,2,3,4] One difficulty has been the credibility gap between analytical predictions and actual in-flight experience. The ubiquitous suggestion of examining Gemini results has produced no data. The flight of Spacecraft 011 on Mission AS-202 on August 25, 1966, has now produced a set of pertinent data which cast doubt on the validity of present RCS propellant budgeting processes.

The flight data quoted herein are contained in "Postlaunch Report for Mission AS-202 (Apollo Spacecraft 011)," MSC, October 12, 1966.# Unless otherwise noted, page, table and figure references used in this memorandum refer to the Command Module (CM) and Service Module (SM) RCS data contained on pages 7-157 to 7-180 of the post-launch report. While this author does not subscribe to all the statements contained therein, they do raise questions about the RCS budgets for long-duration Mission AS-204, the Lunar Orbit Rendezvous (LOR) Mission and operation of the Lunar Module (LM) RCS.

2. Loaded Propellants

Table 7.9-II (page 7-164) shows that the eight SM RCS tanks contained 1.0 to 2.6 percent less than their nominal load of propellant; the total load is off 1.9 percent. (Table 7.9-VIII, page 7-170, shows the four CM RCS tanks are off 0.7 to 1.7 percent, with the total being off 1.3 percent.) It would be interesting to learn the source of these off-loading effects and how such precise measurements of them were made. Generally, loading accuracy is taken as 0.5 percent,* and while the discrepancy (1.4 percent) is not large, it is 35 percent of the allocation (4 percent) for an operational margin on Mission AS-204 (reference 5).

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*An independent study by the author examined variations in tank volumes, bladder expulsion efficiencies, loading temperatures and batch density; the result is that the arbitrary value of 0.5 percent is, indeed, a good estimate.

#Including the data correction in reference 6. [redacted]

3. Gaging Accuracy

The propellant consumed during Mission AS-202 was estimated by two gaging techniques. The PTV gaging technique used pressure-temperature-volume (PTV) measurements of the helium pressurant; this is the gaging system to be used by the astronauts on the LOR Mission. The second technique is based on the firing data and is the (postflight) summation of the firing durations of the several RCS engines. Since an accuracy of two percent was claimed for this technique, it was assumed as the reference for the PTV data. In the original postlaunch report, the firing data indicated 75 pounds more propellant consumed than did the PTV measurements. It was noted that this is less than 10 percent of the 800 pound total, and the error was attributed to the PTV system due to the fact that this specific spacecraft did not have the temperature measurements to correct the PTV readings. However, the revision to the postlaunch report (reference 6) states that the firing data were in error and overestimated total consumption by a factor of two (316 vs 169 lbs). Both values are within 10 percent of the PTV data, but it would seem that closer examination of the data, including a reconstruction of the temperature time history necessary to make both gaging estimates agree with each other, would have uncovered the gross error of the "two percent" firing data. It should be noted that both gaging measurements agree with each other for the CM RCS as shown in Figure 7.9-8; presumably if they are the same, they are correct.

4. Maneuver Dynamics

When the angular accelerations measured during several vehicle maneuvers are compared to the predictions (Table 7.9-IV), they differ by 5 to 13 percent but this is the limit of the measurement accuracy due to the evaluation technique (change of vehicle rates) and short engine pulses (low accelerations). Table 7.9-V shows that the translations (ullage settling maneuvers) differ by 7 to 8 percent between measurements and predictions, but the accuracy of these data is only 10 percent due to granularity (ΔV pulses) and data quality (data dropout). Neither table proves that there are errors in the prediction of vehicle dynamics during RCS maneuvers, but the postflight analysis cannot confirm the predictions to better than 10 percent. Such a gross check is inadequate to verify various refinements of propellant consumption predictions; these include use of such parameters as attitude rate and attitude displacement, and the trade-offs between sequential and simultaneous maneuvers.

5. Maneuver Consumption Rates

Table 7.9-VI lists the SM RCS propellant consumed for eight maneuvers, several of which are discussed in this section.

Roll Control. Propellant consumption for roll control during operation of the Service Propulsion System (SPS) is generally considered as negligible and often is not included in the propellant budget. For instance, one version of the LOR budget assumed a rate of .0045 lb/sec (Table II-8 of reference 2). However, the AS-202 rate was ten times greater than this value; Table 7.9-VI shows 9.2 lbs were consumed on the first SPS firing of 215 seconds for a rate of .043 lb/sec. The 119.3 seconds of SPS operation on Mission AS-204 (reference 5) would therefore require 5.1 pounds of RCS propellant which was not included in the RCS budget. As much as 26 pounds of RCS propellant could be required within the 600 second burn capability of the SPS engine; this amount is approximately equal to the quantity allocated in various budgets for operational margin and/or uncertainties.

Post-Burn Attitude Hold. Table 7.9-VI shows that the (116 second) attitude hold immediately after the deorbit burn of the SPS consumed 3.3 pounds of RCS propellant. This is ten times less than the 35 pounds assigned to this maneuver for Mission AS-204 (reference 5).

SM Jettison Orientation. Table 7.9-VI shows that the SM jettison orientation maneuver consumed 5.4 pounds of RCS propellant. This differs by almost a factor of two from the 8.8 to 10.4 pounds allocated to this maneuver for Mission AS-204 (reference 5).

Attitude Hold. Table 7.9-VI* shows that the 3038 second (50 minute) local vertical attitude hold consumed 46.2 pounds of propellant for a rate of .015 lb/sec or 55 lb/hr. The AS-204 allowance is 7.5 pounds for 3.75 hours of manual local vertical attitude hold (reference 5). This gives a rate of 2.0 lbs/hr, a factor of 25 less than the AS-202 experience!

6. Total Consumption

The previous section discussed propellant consumption predictions which were in error by factors of 2, 10 and 25. However, some predictions, such as roll control and local vertical attitude hold, have been too low; some predictions, such as post-burn attitude and SM jettison maneuver, have been too high; and some predictions, such as attitude accelerations and ullage settlings, have been accurate to within 10 percent. Perhaps propellant budgets contain so many variables that a form of the central limit theorem would result in the total propellant consumption being equal to its predicted value.

Figure 7.9-1* shows that the predicted total consumption for the SM RCS was 257 pounds and the actual consumption was 169 pounds. That is, the actual is 34 percent less than the predicted value! This startling deviation was attributed to "assumptions, estimations and simplifications made in the flight plan budget."

*As corrected by reference 6.

Figure 7.9-8 shows that the CM RCS used 64 pounds of the propellant for reentry while the predicted value was 62 pounds. However, there is very little agreement between the predicted and actual time histories of usage; the predicted usage is 2 to 3 times greater than the actual at certain times during reentry. The AS-202 reentry trajectory was significantly different than predicted because of the lower lift-to-drag ratio (0.28 vs 0.33) and the steeper flight path angle (-3.53° vs -3.48°); this resulted in a 205nm uprange miss distance.* Therefore, the close agreement between predicted consumption (62 pounds) and the actual (64 pounds) might be the result of a coincidence. Or, perhaps, all reentry trajectories consume the same amount of propellant. In either case, there is nothing here to instill confidence in propellant consumption prediction techniques.

7. Conclusions

Because Mission AS-202 was not consumables-limited, was overall successful and had no particular problems with the reaction control systems, there is a danger that these valuable flight data will not be used to critically evaluate the "assumptions, estimations and simplifications" in current use. This memorandum commented on five aspects of the RCS data as shown in Table I. Each of these aspects should be examined to the point where one of the following conclusions can be assigned: invalid data, erroneous predictions, or new information.

TABLE I

SUMMARY OF COMMENTS

Item	Comments
propellant loading	off-loaded 1-3%
propellant gaging	
engine firing durations	1-2% accuracy claimed
Helium PTV	10% error due to temp.
maneuver dynamics	10% data accuracy
maneuver consumption	factors of 2, 10 and 25
total consumption	34% below prediction

The first category, invalid data, anticipates the possibility that scrutiny of the flight data may remove the justification for certain statements and conclusions contained in the postlaunch report. Under the category of erroneous predictions would be included any numerical mistakes as well as improper or incomplete use of available information. The third category, new information, would be used where the best prediction techniques, which were available before launch, did not accurately anticipate the flight results. This last category would lead to revisions of the prediction techniques.

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*Figure 7.11-15 indicates a 600nm downrange miss distance would have resulted if the predicted values occurred; no doubt there is an error in the illustration.

The fact that these flight data are still of current interest and that there is still knowledge to be gained from them can be seen from the following discussions of references 6, 7 and 8, each of which illustrate one of the three possible categories. Unfortunately, they are piecemeal solutions to the problem and raise as many questions as they answer.

An example of the invalid data category is the correction to the postflight report (reference 6). Processing of the Pretoria telemetry data has shown that the previously published propellant consumption data based on the engine firing gaging technique was in error. This raises the following questions: What is the full impact of the fact that the corrected estimate shows that the total propellant consumption is only half of the previous estimate? Is it still valid to attribute the "error" of the PTV system to the lack of temperature measurements? Why didn't the PTV readings uncover the factor two error in the firing data?

As an example of the erroneous prediction category, the November 1, 1966, revision of the AS-204 Mission Modular Data Book (reference 7) uses the results of AS-201 and AS-202 to eliminate the requirement to assign 20 to 60 pounds of RCS propellant to maintain attitude after each SPS burn.* While this was a controversial requirement, it is a good example of the point in question. Were the AS-201 results too inconclusive to revise the requirement? What was the confidence in the information used in the analytical prediction that it could not be corrected without a second flight and an additional six months? Is our knowledge of propellant slosh and control loop dynamics so empirical that certain predictions are valueless? While we now have an answer for the Command Service Module, at least for specific SPS propellant loadings, what confidence can be placed in predictions for the Lunar Module?

The third category, new information, is illustrated by an MSC memorandum (reference 8) which was an attempt to glean new information from the flight results. It examined the roll control channel for both main engine operation and attitude hold; it attributed the unexpected behavior of this channel to longer RCS pulses, asymmetry of the main engine thrust vector, and pitch-roll cross-coupling. But why was the average pulse duration 40 ms instead of 18 ms? And what is the origin of the structural torsional resonance at 14.5 cps? Incidentally, this MSC memorandum made a few comments about the propellant consumption for local vertical attitude hold which should be updated in light of the data correction of reference 6.

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*This led to an AS-204 requirement of having no attitude constraint for 10 minutes after each SPS burn to conserve propellant (reference 5); presumably these periods of uncontrolled attitude will now be eliminated.

These questions can best be answered by a unified approach to the problem which would include those responsible for the conclusions stated in the postlaunch report, those involved in the current analytical predictions and those responsible for the operational aspects of actual RCS usage. Such a study would lead to more critical postflight analysis, more concern for published predictions and a re-examination of the credibility of various budgets and/or allocations.

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Attachment
References

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(See next page)

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